

Spatial distribution and radiative effects of soot in the snow and sea ice during the SHEBA experiment

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[1] Soot observations around the periphery of the Arctic Ocean indicate snowpack concentrations ranging from about 1 to more than 200 ng carbon/g snow (ngC/g), with typical values being near 40–50 ngC/g. Values of this magnitude would significantly affect not only the albedo and transmissivity of the ice cover but also surface melt rates and internal heat storage in the ice. During the Surface Heat Budget of the Arctic Ocean (SHEBA) drift, there was concern that soot emitted from the ship could adversely impact the heat and mass balance measurements, producing results that would not be representative of the region as a whole. To investigate this possibility, a series of soot measurements was carried out starting in the spring of 1998 during the time of maximum snowpack thickness. On the upwind side of the ship, where the heat and mass balance program was carried out, soot concentrations averaged over the depth of the snowpack spanned a range from 1 to 7 ngC/g, with average values of 4–5 ngC/g. On the downwind side, concentrations increased to 35 ngC/g and above. Measurements made up to 16 km from the ship yielded average background soot levels of approximately 4.4 ngC/g, with a standard deviation of 2.9 ngC/g evenly distributed throughout the different snow layers. These concentrations were not statistically distinguishable from the values measured in the observing areas on the upwind side of the ship. This indicates that soot concentrations in the central Arctic Basin are substantially lower than those reported for the coastal regions and are not sufficient to produce a significant decrease in the albedo. Although measurements of sea ice samples gave similarly low values, parameter studies show that the snow soot levels could be significant if the summer melt caused all the soot to be concentrated at the ice surface. *INDEX TERMS*: 1863 Hydrology: Snow and Ice (1827); 4207 Oceanography: General: Arctic and Antarctic Oceanography; 4552 Oceanography: Physical: Ocean Optics; 9315 Information Related to Geographic Region: Arctic Region; *KEYWORDS*: soot, snow, sea ice, albedo, Arctic haze

1. Introduction

[2] Soot has been identified as a highly absorptive material that when embedded in a snowpack can have a significant effect on the bulk optical properties [Warren and Wiscombe, 1980]. Observations carried out around the periphery of the Arctic Ocean [Clarke and Noone, 1985] indicate snowpack concentrations ranging from about 1 to more than 200 ng carbon/g snow (ngC/g), with typical values near 40–50 ngC/g. Values of this magnitude would affect not only the albedo and transmissivity of the sea ice cover, but also surface melt rates and internal heat storage in the ice. Albedo parameterizations including soot have been developed for use in climate models [Marshall, 1989; Marshall and Oglesby, 1994], but for useful application they require a measure of the actual soot concentration and

distribution in the snow. Observations in the central Arctic are sparse, and it is presently unclear whether concentrations are high enough to produce a significant effect on the radiative energy balance.

[3] During the planning for the Surface Heat Budget of the Arctic Ocean experiment (SHEBA), there was a serious concern that soot emitted from the ship might adversely impact the heat and mass balance measurements, producing results that would not be representative of the region. To investigate this question, a survey of the soot content of the snowpack was carried out starting from late March to late May 1998, during the time of maximum snowpack accumulation. This provided an integrated measure of soot accumulation since the previous autumn when the station was established. The objectives of the present study were to determine ambient levels of soot concentration in the Central Arctic and to investigate whether additional soot emitted by the ship and deposited in the snowpack would be high enough to

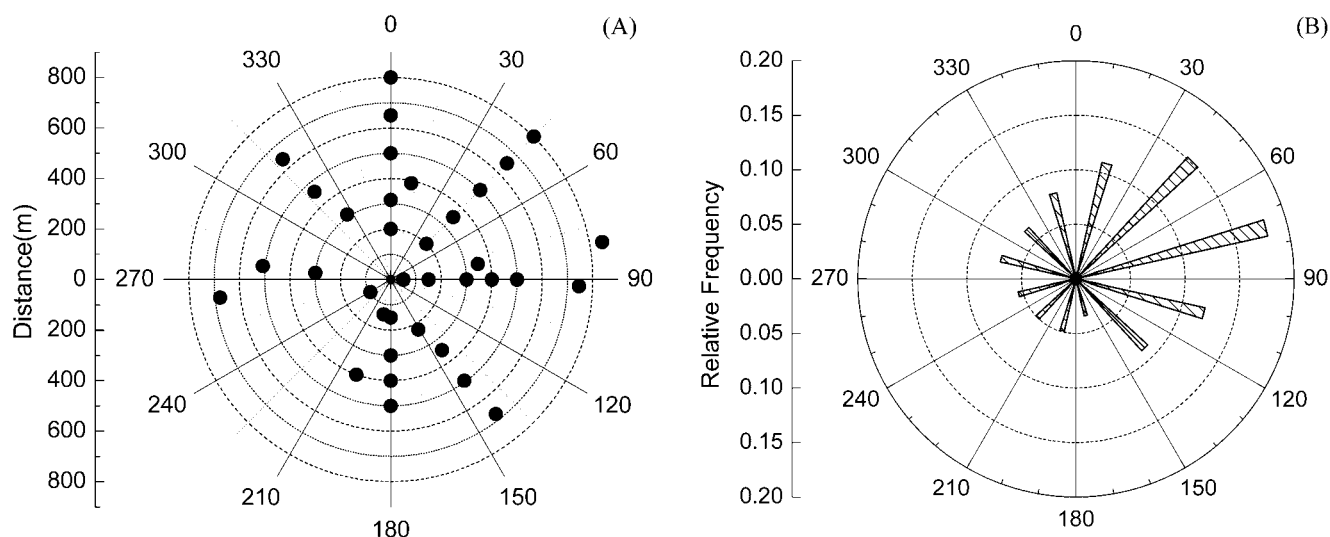


Figure 1. (A) Polar plot of the location of the measurement sites during May 1998. The distance scale (in m) is indicated along the left edge, and the numbers around the outside of the circle are the direction angles relative to north. The ship was located at the center of the array. (B) Wind rose for 2 m elevation courtesy of R. E. Moritz and the SHEBA Project Office. The radial bars indicate relative frequency computed from observations at 10-min intervals.

cause a significant decrease in spectral albedos and melt rates.

2. Observations

[4] Soot concentration was measured using the filtration method described by *Clarke and Noone* [1985], *Warren and Clarke* [1990], and *Bond et al.* [1999]. Snow and ice samples were gathered at various locations centered on the ship (Figure 1) out to a radius of about 800 m. At these sites the entire depth of the snowpack was sampled by removing a cylindrical core. The snowpack thickness was typically 40 cm. Additional samples for determination of background levels were also obtained on traverses out to 16 km from the ship. These samples were collected from individual layers and placed in clean plastic bags. The snow was collected in clean glass sample jars, melted rapidly in a microwave oven, and the meltwater filtered through $0.4\ \mu\text{m}$ nucleopore filters. The filters were then compared visually with a standard filter set of known loading to determine the mass of soot deposited on each of them. Selected ice samples were obtained with a CRREL ice auger and processed in the same way as the snow. By increasing the volume of snow or ice that was processed, very low soot concentrations could be measured.

[5] The wind direction was primarily from the northeast and east-northeast (Figure 1B), which blew soot emitted by the ship away from the main observation area on the eastern side of the ship. The ship's personnel assisted the experiment by limiting trash burning and engine tests to times when the wind was blowing away from the observation area. This was very effective in preserving the pristine condition of the observation area.

[6] *Bohren* [1986] has demonstrated that there can be considerable uncertainty in the absorption efficiency of soot depending on the size, shape and porosity of the particles

producing uncertainties of a factor of two or more in the absorption per unit mass of soot of various types. The standard filter set we have used has interpreted the mass of soot on each filter by assuming an absorption efficiency of $6\ \text{m}^2/\text{g}$, which is based on observations of fresh smoke [*Dobbins et al.*, 1994] and calibration studies by *Bond et al.* [1999]. The determination of soot concentration is derived from an optical measurement such that the mass derived produces the proper amount of absorption by the soot deposited on the filters. Thus, when we quote a measured soot concentration in nanograms per gram, this can be thought of as an optical-equivalent mass that yields an absorption coefficient suitable for use in radiative transfer calculations. Since this is the present application, the sensitivity to the structure of the soot particles is minimized compared to that which would be present if a different technique were used.

[7] In the present context, a concentration of $15\ \text{ngC/g}$ distributed uniformly in an optically thick snow layer produces a depression in the albedo at $500\ \text{nm}$ (α_{500}) of about 0.01 for a grain radius of $100\ \mu\text{m}$ [*Grenfell et al.*, 1994]. In view of the natural fluctuations in α_x due to variations in local surface slope and shadowing in a natural snowpack, this is considered the threshold of detectivity. Since $500\ \text{nm}$ is the wavelength at which the albedo is most sensitive to soot, concentrations below this level will produce a negligible effect on wavelength-integrated snow albedo.

3. Results

[8] On the station floe upwind of the ship, where the heat and mass balance program was carried out, depth averages of soot concentrations in the snow spanned a range from 1 to $10\ \text{ngC/g}$ with mean values of $4\text{--}5\ \text{ngC/g}$. The lowest values ($<7\ \text{ngC/g}$) were found in the clean sector, which included the standard albedo observation area and most of

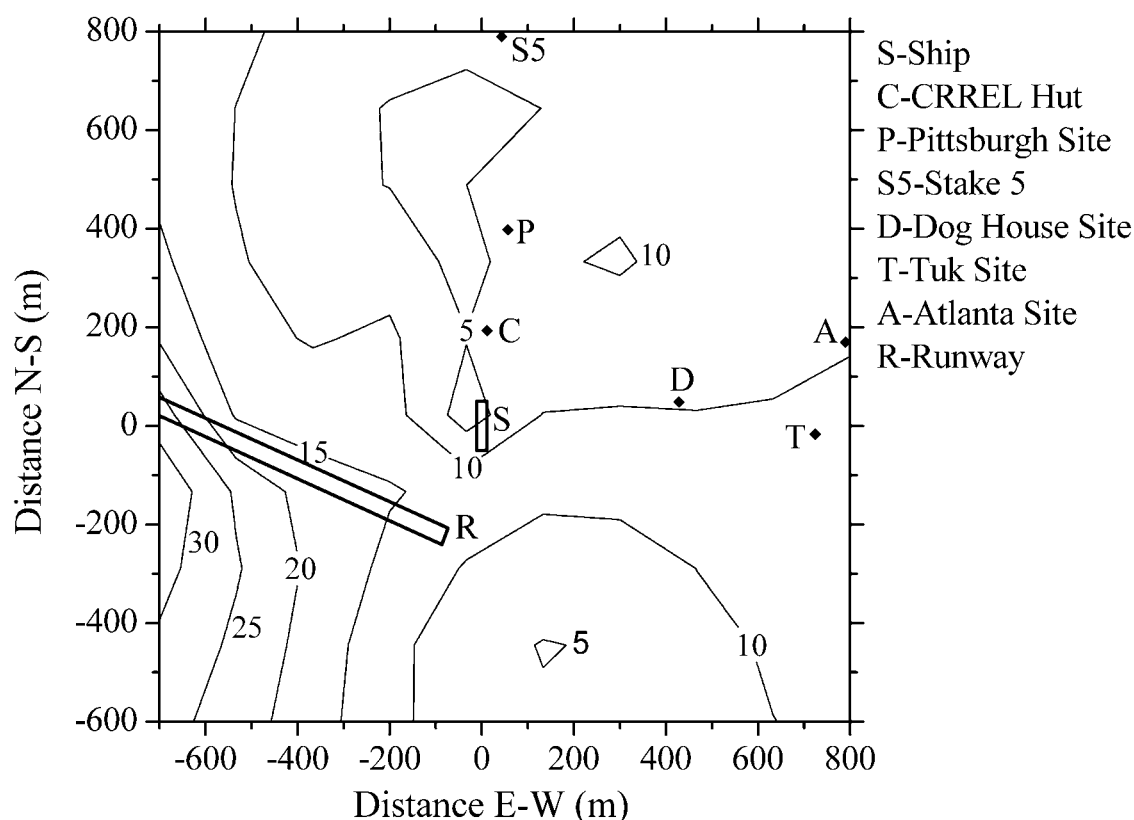


Figure 2. Contours of average soot concentration in the snow (in ngC/g). The locations of the various observational and operational sites are identified in the legend.

the SHEBA heat and mass balance sites. A significant increase was observed on the downwind side of the ship with values increasing to more than 35 ngC/g adjacent to the airplane landing strip. Contours of soot concentration are shown in Figure 2.

[9] To determine natural background levels and to investigate the horizontal and vertical variations of soot over a larger area, snow samples were collected during extensive surface traverses out to 16 km from the ship in late March and April 1998. Concentration values obtained from different levels in the snowpack are shown in Figure 3. The average for all samples was 4.4 ngC/g with a standard deviation of 2.9. These results show that concentrations upwind of the ship were essentially the same as the background levels. It is also apparent that soot concentrations in the central Arctic are substantially lower than those that have been reported previously for the coastal regions.

[10] Within the limits of the natural variation, the average soot values did not differ significantly from one layer to another. This indicates that the deposition of soot in the snow was quite uniform throughout the year. Assuming that this is true in general and that the mean soot concentration is as given above, the total columnar soot concentration is given by the following formula: $C_{\text{soot}} = 4.4 \times 10^{-9} \rho_{\text{snow}} z_{\text{snow}}$, where C_{soot} is the total columnar concentration in kg/m², and ρ_{snow} and z_{snow} are the snow density (kg/m³) and snow depth (m) respectively. Thus for a snow density of 320 kg/m³ typical of the late winter and early spring

snowpack in the vicinity of the SHEBA site, $C_{\text{soot}} = 4.2 \times 10^{-7}$ kg/m² for a 0.3 m thick layer. The associated uncertainty including the precision of the mean soot concentration and the variation in snow density for cold wind packed snow is $\pm 2.8 \times 10^{-7}$.

4. Discussion

[11] Previous theoretical and observational studies [Warren and Wiscombe, 1980; Grenfell et al., 1994] indicate that soot levels in an optically thick snowpack must exceed about 15 ngC/g to produce a 0.01 decrease in albedo at 500 nm. Since this is the wavelength region where ice is least absorbing, absorption by soot has the strongest effect. At both infrared and ultraviolet wavelengths, ice becomes a strong absorber [Grenfell and Perovich, 1981; Perovich and Govoni, 1991] and the addition of soot is masked. Contamination levels found in the snow at the heat and mass balance sites and other observational areas around the ship thus had little, if any, detectable effect on albedos or the melt progression of the snow cover. Further, the transect data show that soot levels in the “clean air sector” were essentially at background levels, indicating that efforts by the ship’s crew and station personnel to minimize the effects of the ship on the local energy balance were successful and the optical properties of the snow were representative of the undisturbed surface.

[12] After the snow had melted, ice samples were observed using the same technique. The average value was 5.5 ngC/g

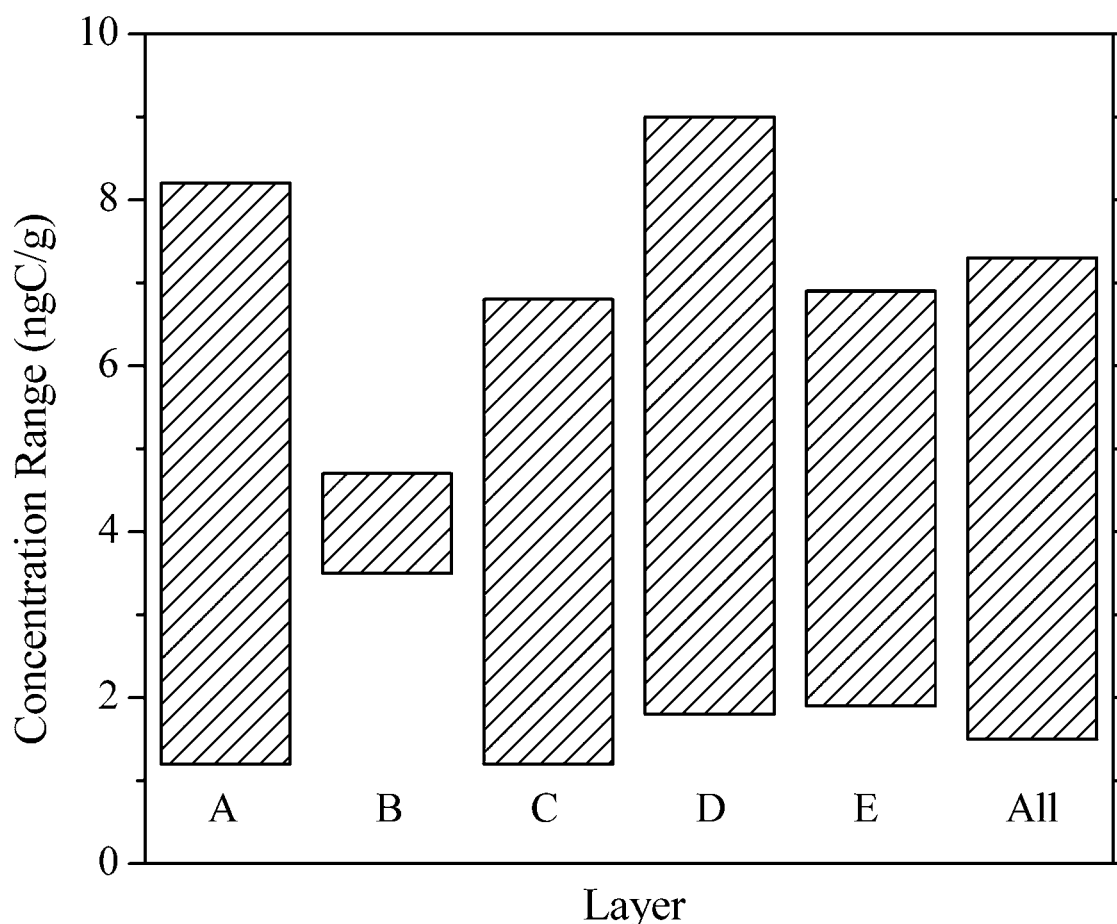


Figure 3. Soot concentration in the snow between 4 and 16 km from the ship. The layers are labeled A–E starting from the top of the snowpack. Each layer represents a separate deposition event. The height of the bars shows the range covered by one standard deviation about the mean. The category “All” includes all the layers of the entire remote sample set and has an average value of 4.4 ngC/g, with a standard deviation of 2.9 ngC/g.

with a standard deviation of 2.6 ngC/g. Unfortunately, small transparent particles present in the ice tended to clog the filters making the observations very time consuming. These particles may have obscured some of the soot particles, however, scattering by the filter should dominate over scattering by the clogging particles. We conclude that the concentration of soot at the surface of the summer ice was not large and that contamination from the ship was insignificant during the summer.

4.1. Sensitivity Studies

[13] Although it is unlikely that contamination from the ship affected the heat and mass balance at the SHEBA site, it is possible that natural background levels of soot could modify the melt cycle of snow-free ice, depending on how much of the soot was scavenged from the melted snow by the upper few cm of the ice. While we suspect that much of the soot originally contained in the snow cover was carried away by meltwater, some portion of it must have been left behind and deposited in the upper layers of the underlying ice. Because the problem with the particles made it very difficult to measure sea ice samples, we have carried out a set of theoretical sensitivity studies designed to determine

the effects of varying concentrations and vertical distributions of soot on the albedo, transmissivity, and internal heating of the ice.

[14] The model studies were designed to provide an upper limit for the effects by considering cases where the scavenging efficiency was very high. They were carried out using a multilayer 4-stream radiative transfer model [Grenfell, 1991]. The ice structure profiles and scattering coefficients specified in the model, shown in Figure 4, were derived from field data and from structural parameters used to reproduce spectral albedos of clean multiyear ice observed on 13 July 1998.

[15] The inherent optical properties of soot were taken from the study of Warren and Clarke [1990]. The soot distributions used in the study are shown in Figure 5. In the first case, the soot was assumed to be concentrated in the uppermost centimeter of the ice with concentrations varying from 0 to 1000 ngC/g, a value that would result if the soot from approximately 1 to 2 m of snow were condensed into the top of the ice. In the second case, a soot loading of 300 ngC/g in the top 1 cm was redistributed into layers of thicknesses 2, 4, 6, 8, and 10 cm maintaining a constant total soot mass.

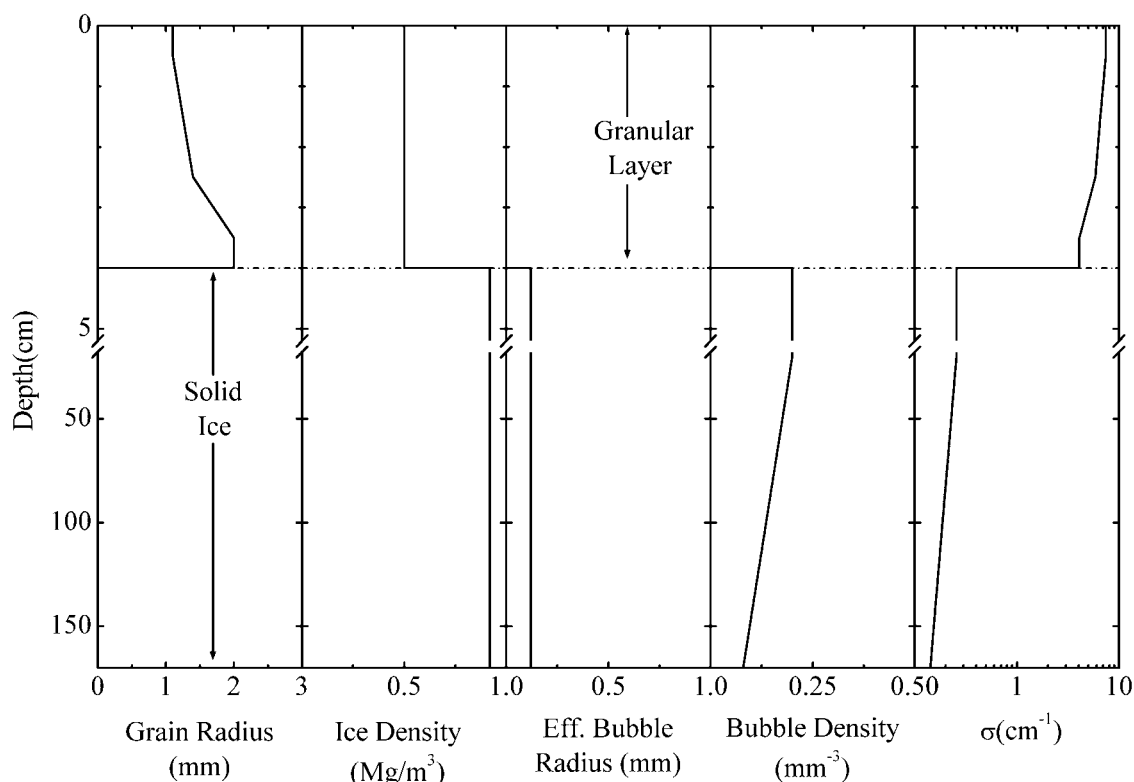


Figure 4. Depth profiles of ice structure used in the model. σ is the volume scattering coefficient (cm^{-1}) at visible and near-infrared wavelengths.

[16] Selected results for albedo and transmissivity of net irradiance, $T(F_{\text{net}})$, are shown in Figures 6 and 7. When the soot was deposited in the upper cm of the ice (Figure 6), the model predicted that the maximum reduction in spectral albedo near 500 nm would be 0.010, 0.028, 0.045, and 0.084 for concentrations of 100, 300, 500, and 1000 ngC/g, respectively. The corresponding decrease in transmissivity through the upper 10 cm of the ice ranged from 0.042 to 0.307.

[17] The effect of distributing a constant mass of soot over progressively thicker surface layers is shown in Figure 7. The largest changes occurred when the soot was concentrated near the surface. The maximum albedo decrease at 500 nm was 0.034 relative to clean ice, and the corresponding decrease in transmissivity was 0.128. Note that the effect of soot on the apparent optical properties of the ice became progressively smaller at longer wavelengths as rapidly increasing absorption by the ice exceeded additional absorption by the soot. The transmission curves at 1000 nm in both Figures 6B and 7B are essentially flat illustrating that the influence of soot for the concentrations considered here is negligible at that wavelength.

[18] We also examined the effects of soot on the rate of solar heating in the upper 10 cm of the ice, where most of the energy for surface melting is absorbed. Under cloudy conditions we found that a concentration of 100 ngC/g in the upper cm of the ice produced a 7% increase in the heating rate, and 300 ngC/g produced a 20% increase. When the 300 ngC/g was spread uniformly through the upper 10 cm of the ice, there was still a 12% increase in

the amount of shortwave energy absorbed, reflecting both the lower albedo and the decreased energy transmission to deeper levels of the ice. Thus the soot causes a vertical redistribution of solar energy deposition within the ice.

4.2. Comparison with Antarctic Measurements

[19] Similar observations have been carried out at inland Antarctic stations (South Pole and Vostok) as reported by Warren and Clarke [1990] and Grenfell et al. [1994]. The background soot level upwind of South Pole station was found to be about 0.3 ngC/g with a corresponding value of about 1–2 ngC/g upwind of Vostok Station. As for the present case, significant increases in soot levels were measured in the snow downwind of the stations due to power plant emissions and vehicular activity. The background levels in the present study were approximately 3 to 5 times greater than the Vostok values and are associated with a total snow accumulation of about 5 times as large (10–13 g/cm² yr). This suggests that the soot accumulation in the Arctic snowpack cannot be understood simply in terms of a different accumulation rate resulting in a different dilution of the soot in the snow, and it is most likely that the source of the soot is significantly more intense in the Arctic. Arctic haze [Cess, 1983; Blanchet and List, 1987] is a prime candidate for the source of the difference between the results for the Arctic and Antarctic. A determination of the scavenging efficiency of haze by the formation and deposition of snow is beyond the scope of this work; however, it appears that the mass of soot in the Arctic atmosphere

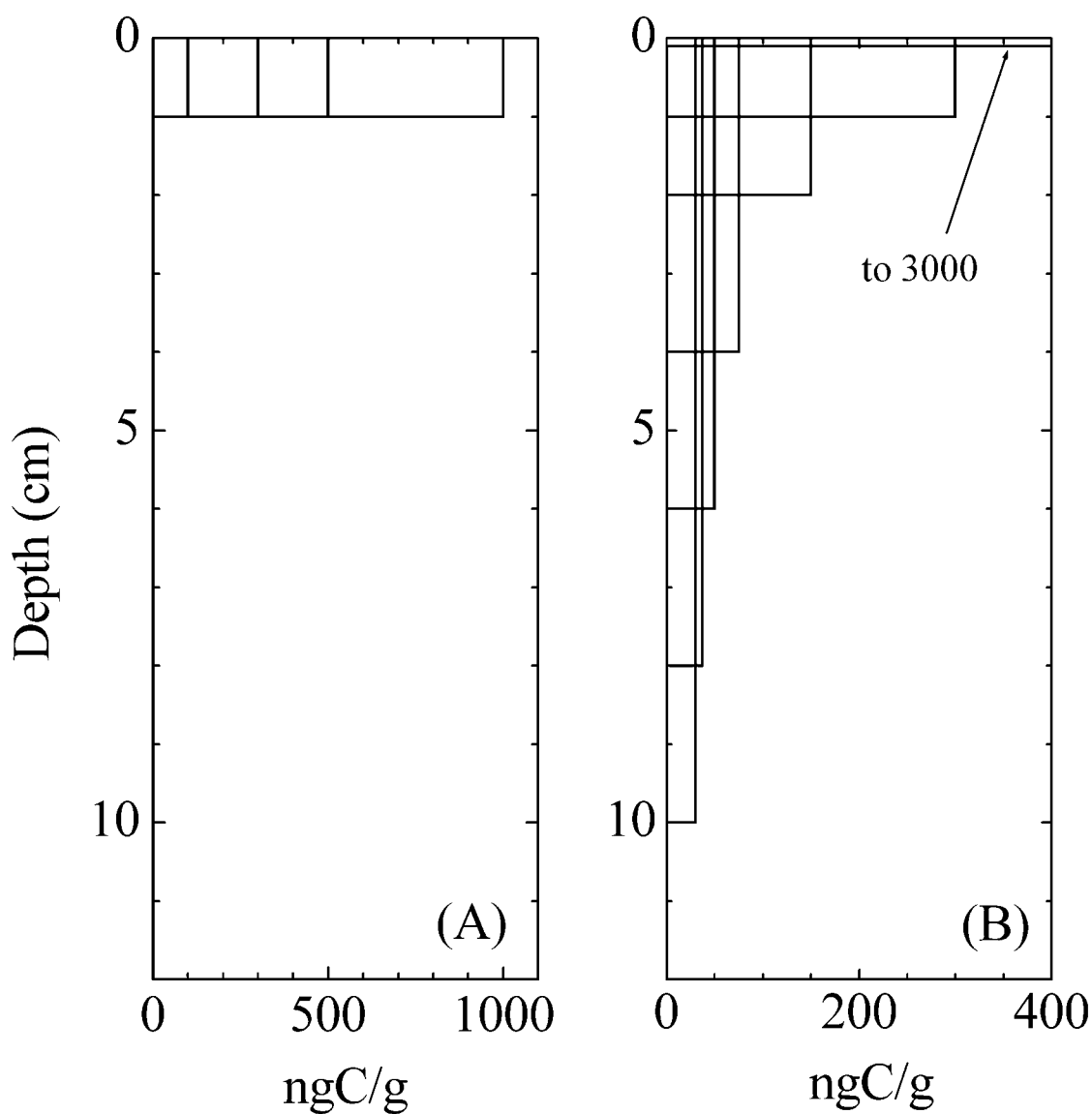


Figure 5. Vertical profiles of soot distribution. (A) Varying concentration in a 1 cm surface layer (0, 100, 300, 500, and 1000 ngC/g). (B) Constant total soot mass (300 ngC/g in a 1 cm layer) distributed over layers of thicknesses 0.1, 1, 2, 4, 6, 8, and 10 cm.

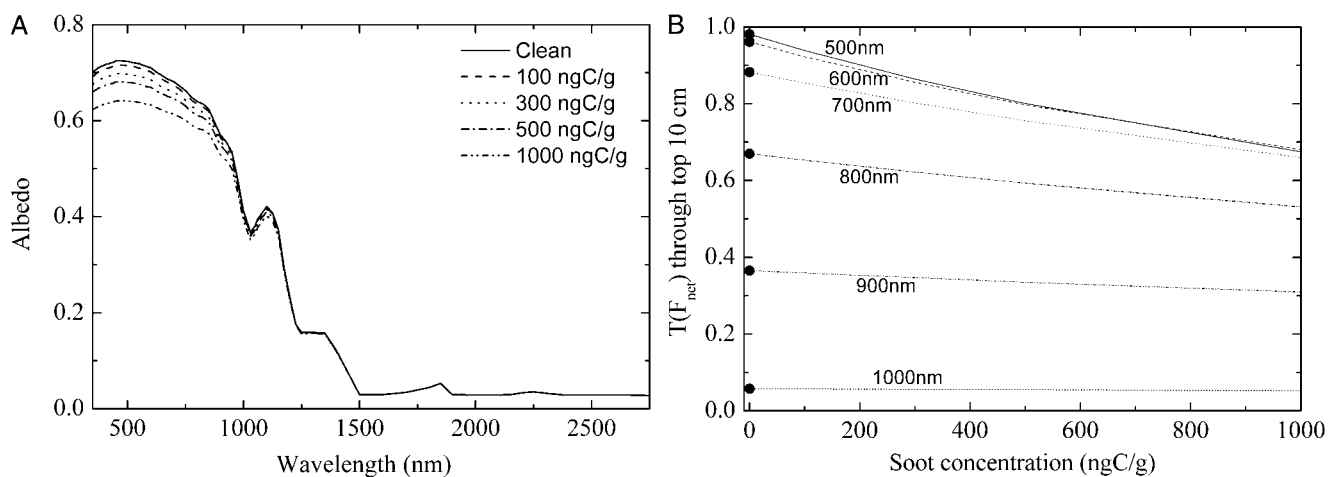


Figure 6. (A) Albedo and (B) transmissivity of the net irradiance (T) for varying soot concentrations in a 1 cm surface layer as shown in (A).

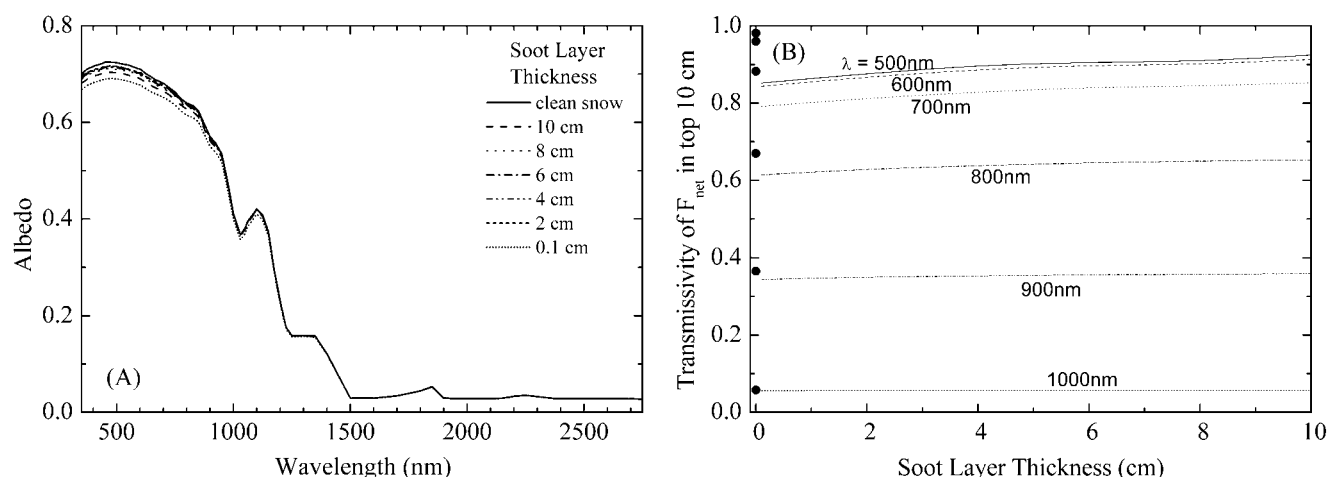


Figure 7. (A) Spectral albedo and (B) transmissivity (T) at selected wavelengths for varying vertical distributions of soot (see Figure 6B) with constant total mass equivalent to 300 ngC/g in a 1 cm snow layer. The solid dots in (B) indicate the values for clean snow at each of the six wavelengths in corresponding order.

is sufficient to explain the observed soot levels in the snow.

5. Conclusions

[20] The levels of soot in the snow throughout the observational area in the vicinity of the ship at the SHEBA station were much lower than those that have been reported for coastal areas of the Arctic Basin and were essentially the same as the natural background soot content of the surface in the region. The background levels were higher than at remote Antarctic sites probably due in large part to arctic haze, but they were still too low to reduce the albedo of the sea ice or to affect the heat and mass balance. If all the soot were concentrated in the upper layers of the ice upon melting, however, the summer ablation would be accelerated.

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